Final Report: Planetary Gearset Dynamics in Military Helicopters (37382-EG-YIP)

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Objectives

This research is a comprehensive analytical and computational investigation of the dynamic response of planetary gears (Figure 1). In military helicopters, planetary gears are typically the last stage gear reduction whose output drives the main rotor. Their dynamics dominate the cabin noise. Furthermore, the frequency of the noise is in the range most audible by humans. With deeper understanding of planetary gear dynamics, the goals are to reduce the noise, vibration, and weight of helicopter planetary gears while simultaneously increasing their reliability. This project developed lumped-parameter and finite element analysis tools for planetary gears (Figure 2). These tools are notably lacking despite the importance of planetary gears in helicopters, cars, heavy machinery, marine vehicle and other applications. Planetary gears have received little prior research attention as most gear dynamics studies address the simpler case of a single pair of meshing gears. Thus, the potential for scientific advancement and near-term practical application of the results is excellent. The unique computational tool available for this effort made the objectives achievable.

Approach

The most difficult aspect of gear dynamics is modeling the tooth contact. This study used specialized finite element modeling to capture the tooth mesh forces and contact mechanics with an accuracy beyond that achievable with any conventional finite element tool. The limitation of conventional finite elements is that they require prohibitively refined meshes along the tooth surface because of the narrow contact region and the precise tooth surface description that gear dynamics demands. A unique semi-analytical formulation combining analytical and finite element solutions with advanced contact modeling is used in this work. The remarkable advantages are that one can define the tooth surface geometry with arbitrary precision, model the contact more realistically, and obtain excellent results with a relatively coarse mesh (Figure 3). The reduced model size allows dynamic *response* analyses (as opposed to static analyses or vibration mode studies). Planetary gear dynamic response analyses of the fidelity achievable with this model do not exist.

In a parallel effort, an idealized, lumped-parameter model that represents the gears as rigid bodies interconnected by springs modeling the tooth meshes is employed (Figure 2b). This simpler model complements the computational model to capture the critical dynamic phenomena and provide a tool suitable for practical design/analysis as well as basic research.

Significance and Army Value

Measured helicopter cabin acoustics reveal that planetary gear vibration is the dominant source of cabin noise. Figure 4 shows that all dominant peaks in the helicopter noise spectrum are at the planetary gear mesh frequency and its harmonics. Planetary gear induced cabin noise, which can exceed 100 dB, results in operator fatigue, communication difficulty, discomfort, and health risks from extended exposure. Additionally, the dynamic loads reduce reliability and durability while the additional weight needed to sustain these loads reduces payload. These concerns limit helicopter effectiveness in military and civilian applications. Although planetary

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13. ABSTRACT (Maximum 200 words)

This research is a comprehensive analytical and computational investigation of the dynamic response of planetary gears. In military helicopters, planetary gears are typically the last stage gear reduction whose output drives the main rotor. Their dynamics dominate the cabin noise. Furthermore, the frequency of the noise is in the range most audible by humans. With deeper understanding of planetary gear dynamics, the goals are to reduce the noise, vibration, and weight of helicopter planetary gears while simultaneously increasing their reliability. This project will also develop lumped-parameter and finite element analysis tools for planetary gears. These tools are notably lacking despite the importance of planetary gears in helicopters, cars, heavy machinery, marine vehicle and other applications. Planetary gears have received little prior research attention as most gear dynamics studies address the simpler case of a single pair of meshing gears. Thus, the potential for scientific advancement and near-term practical application of the results is excellent. The unique computational tool available for this effort makes the objectives particularly achievable.

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gear induced cabin noise is a major problem, it is currently addressed by *ad hoc* design guidelines, many of which rely on empirical observations rather than engineering understanding. The technical basis for more advanced design is lacking because planetary gears have received much less research attention due to their complexity. The modeling and analysis of critical dynamic behavior from this research provides more firm scientific foundation for helicopter transmission design and analysis that is currently lacking. The project has developed two unique analysis tools: 1) a validated computational tool uniquely suited to gear dynamics, and 2) an analytical model required for early design use by helicopter contractors and further fundamental research.

The Army Research Lab Vehicle Technology Center at NASA Glenn Research Center (directed by Dr. Bob Bill) has active research in helicopter transmission dynamics. The principal investigator (R. G. Parker) spent a recent summer on-site with ARL staff initiating this research. We maintain close communication with ARL research staff. In particular, meetings with Tim Krantz of ARL are held approximately quarterly. Mr. Krantz provides guidance on practical concerns communicated to him by Army helicopter contractors, design data for model development, and experimental results from ARL and contractor testing. We have provided data to Mr. Krantz for his presentations to ARL staff and the Army Technical Advisory Board. Mr. Krantz provides a crucial link to Army contractors to aid technology transfer and ensure the work addresses relevant Army helicopter concerns.

Accomplishments

The finite element approach has been validated against single-mesh gear dynamics experiments with exceptional success. Complex, nonlinear experimental phenomena were predicted with strong correlation that was not achievable with existing analytical or computational tools. Figure 5 compares the dynamic response amplitude of a gear pair from experiments and finite element analysis. The obvious nonlinear jump phenomena and dangerous secondary resonances at speeds 1/2 and 1/3 of the primary resonance speed near 2700 Hz are accurately predicted by finite element. The root cause of the nonlinearity is contact loss at the tooth mesh.

A rigorous examination of planetary gear vibration modes using the lumped-parameter model exposed the highly structured natural frequency spectrum and vibration mode properties. In particular, only three types of mode are possible: rotational modes where the sun, carrier, and ring execute pure rotation; translational modes where these element execute pure translation; and planet modes where the sun, carrier, and ring have no motion and only the planets move. Rotational, translational, and planet modes have natural frequency degeneracies of one, two, and N-3 (where N is the number of planet gears). This well-defined free vibration structure is a result of the cyclic symmetry of planetary gears. Identification of these unique natural frequency and vibration mode properties is of basic importance for further analysis of planetary gear vibration issues.

A finite element model of the Army OH-58 Kiowa planetary gear (Figure 2a) has been developed and verified with a collection of test cases. This includes careful attention to modeling the sun, carrier, and planet bearing stiffness and damping. Much of this modeling was developed with input from ARL and their experience with helicopter transmissions. The study is the most comprehensive dynamic analysis of a planetary gear system available and provides a benchmark that has been notably lacking in the literature. Natural frequency analyses yield excellent agreement with the lumped-parameter model, building confidence in both (Table 1). Dynamic response analyses across a wide range of operating speeds and torques reveal unique resonant behavior caused by the time-varying tooth mesh stiffness as the number of teeth in contact at each mesh changes. Figure 6 shows a sample result of the planet and sun gear deflection spectra for a range of operating speeds (i.e., mesh frequencies).

Dynamic response analyses across a wide range of operating speeds and torques reveal unique behavior caused by the constantly changing number of teeth in contact at each mesh. These have been explained physically.

The dynamic analyses reveal that response in certain vibration modes can be suppressed by appropriate selection of numbers of teeth and planet gear angular position. For example, Figure 6b shows that the even harmonics of the sun gear deflection can be eliminated with appropriate selection of the number of gear teeth. This appears to be a highly effective means to reduce vibration in narrow speed range applications such as helicopters. This observed phenomenon has been analytically explained and reduced to simply applied formulae to predict which modes can be suppressed. These results are immediately applicable to current designs.

Tooth stress analyses have been completed for the Army Kiowa. The ring gear stress distribution is shown in Figure 7. Notice that large stresses are generated far from the planet-ring mesh points, in contrast with conventional wisdom. We have experimental data from ARL at NASA Glenn for this system. A comparison of experiments and analyses shows that accurate stresses can be predicted. This is significant, as stress is an especially difficult quantity to compute under dynamic conditions. The correlation process revealed important modeling issues that must be accounted for in future studies.

A rigorous examination of the sensitivity of planetary gear natural frequencies and vibration modes using the lumped-parameter model has been conducted. Using the highly structured natural frequency spectrum and vibration mode properties developed under this project (see 1998 ARO Progress Report), we derived particularly simple expressions for how the free vibration properties change with model parameters. These results also have immediate design use. A computer code to determine and plot the natural frequencies, vibration modes, and sensitivities to design changes has been developed and will ultimately be available to ARL and Army contractors.

Technology Transfer

Dissemination of the findings to Army staff, helicopter contractors, other industries, and the research community has occurred in a variety of ways. As mentioned earlier, close contact is maintained with ARL staff at NASA Glenn. In 1998, the research was presented at a Glenn Research Center seminar attended by ARL staff, Sikorsky engineers, and gear researchers. Additionally, Tim Krantz of ARL and I have visited Sikorsky twice to discuss the project. We have also traveled to General Motors (whose interest in planetary gears is for automotive transmissions) to explore potential experimental cooperation. In 1999, the results were presented at a Glenn Research Center discussion group attended by ARL staff and Sikorsky's Chief of Transmission Systems.

The research findings are presented twice annually to an industry consortium of approximately thirty companies who are members of the Ohio State Gear Research Lab (D. Houser, Director). In 1998, research findings were presented at the ASME Power Transmission and Gearing Conference. In 1999, we presented two papers at the 4th World Congress on Gearing and Power Transmission and another at the ASME Biennial Conference on Vibration and Noise. Two additional papers have been accepted for ASME gear conferences to be held in 2000. One paper from this work has been published this year in the *ASME Journal of Vibration and Acoustics*, four papers in the *Journal of Sound and Vibration*, and one in the *ASME Journal of Mechanical Design*. Two other papers are under review for publication.

List of Publications

Journal

J. Lin and R. G. Parker 1999 Journal of Vibration and Acoustics 121, 316-321. Analytical Characterization of the Unique Properties of Planetary Gear Free Vibration.

J. Lin and R. G. Parker 1999 Journal of Sound and Vibration 228(1), 109-128. Sensitivity of Planetary Gear Natural Frequencies and Vibration Modes to Model Parameters.

J. Lin and R. G. Parker 1999 (accepted) Journal of Sound and Vibration. Structured Vibration Characteristics of Planetary Gears with Unequally Spaced Planets.

R. G. Parker, S. M. Vijayakar and T. Imajo 1999 Journal of Sound and Vibration (accepted). Nonlinear Dynamic Response of a Spur Gear Pair: Modeling and Experimental Comparisons.

R. G. Parker 1999 (accepted) Journal of Sound and Vibration. A Physical Explanation for the Effectiveness of Planet Phasing to Suppress Planetary Gear Vibration.

R. G. Parker, V. Agashe and S. M. Vijayakar 1999 (accepted) ASME Journal of Mechanical Design, Dynamic Response of a Planetary Gear System Using a Finite Element/Contact Mechanics Model.

Conference

R. G. Parker, V. Agashe and S. M. Vijayakar 1999. Proc. of the 4th World Congress on Gearing and Power Transmission, Paris. 2103-2114 Computational Analysis of Planetary Gear Dynamics.

J. Lin and R. G. Parker 1999. Proc. of the 4th World Congress on Gearing and Power Transmission, Paris. Sensitivity of Planetary Gear Natural Frequencies and Vibration Modes to Model Parameters.

J. Lin and R. G. Parker 1999 ASME Biennial Conference on Vibration and Noise, Las Vegas. Natural Frequencies and Vibration Mode Sensitivity in Planetary Gears.

R. G. Parker, S. M. Vijayakar and T. Imajo. 2000 ASME Power Transmission and Gearing Conference, Baltimore. Nonlinear Dynamic Response of a Spur Gear Pair: Modeling and Experimental Comparisons.

J. Lin and R. G. Parker. 2000 ASME Power Transmission and Gearing Conference, Baltimore. Natural Frequency Veering in Planetary Gears.

Scientific Personnel

- R. G. Parker, PI: Received the Presidential Early Career Award for Scientists and Engineers (presented at the White House) and NSF CAREER Award in 1999
- Dr. Sandeep Vijayakar - research scientist (President of Advanced Numerical Solutions)
- Jian Lin - Ph.D. candidate
- Vinayak Agashe - received MS degree, 1998
- Terumasa Imajo - visiting scholar
- Yuanjie Wu - graduate student
- Li Ning - Visiting scholar

Report of Inventions

None

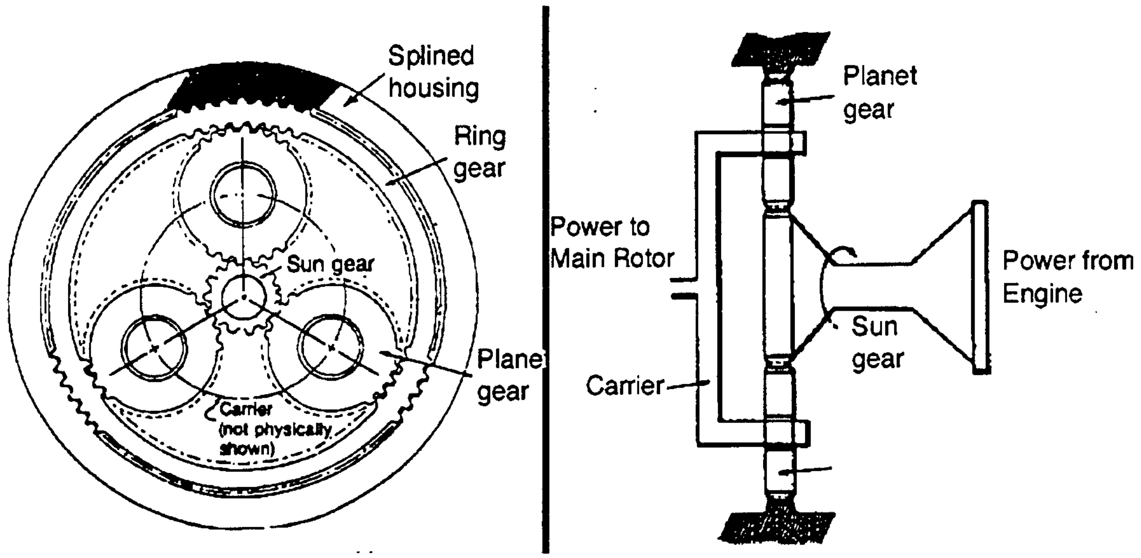

Figure 1: Helicopter planetary gear.

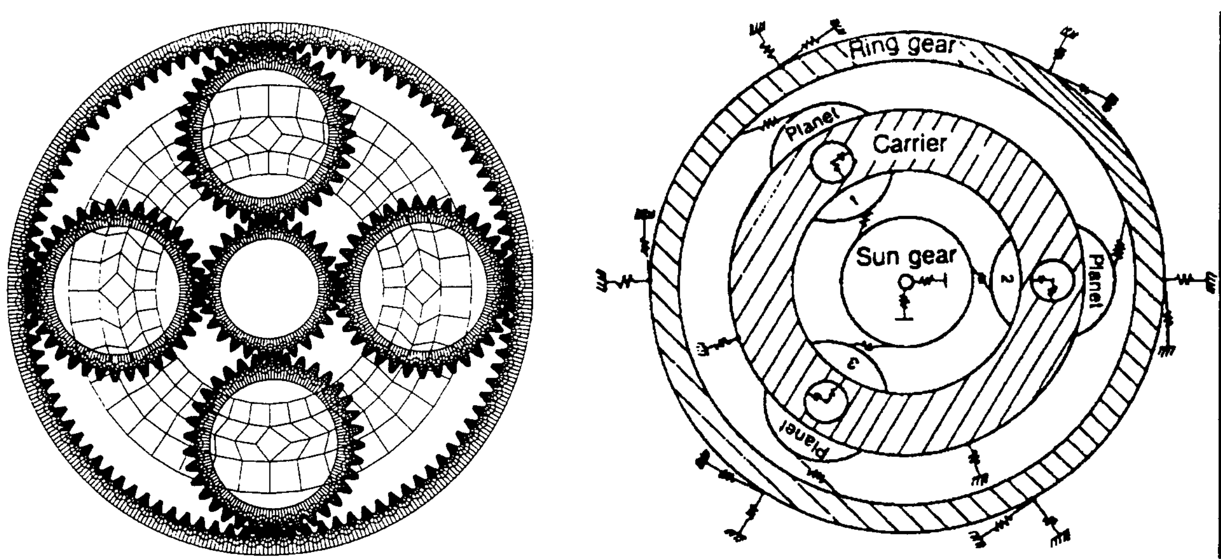

Figure 2: (a) Finite element model. (b) Lumped parameter model used for analytical investigation.

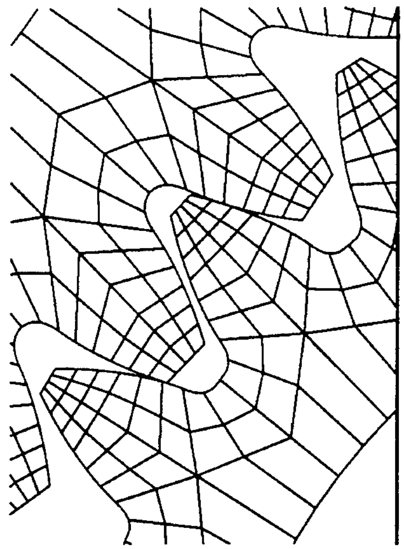

Figure 3: Close-up of tooth mesh. The mesh refinement is much less than what is required with conventional finite element analysis.

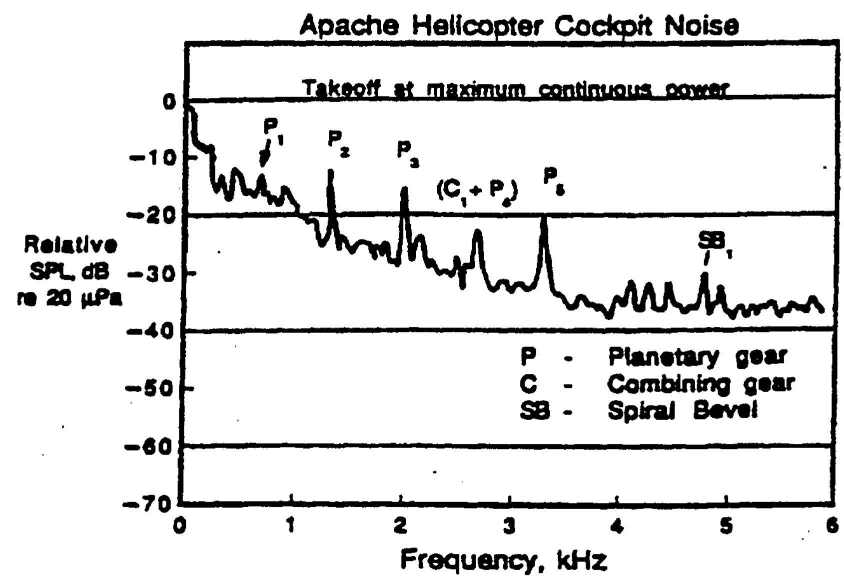

Figure 4: Spectrum of measured helicopter cabin noise. The peaks labeled P_i indicate noise resulting directly from the planetary gear.

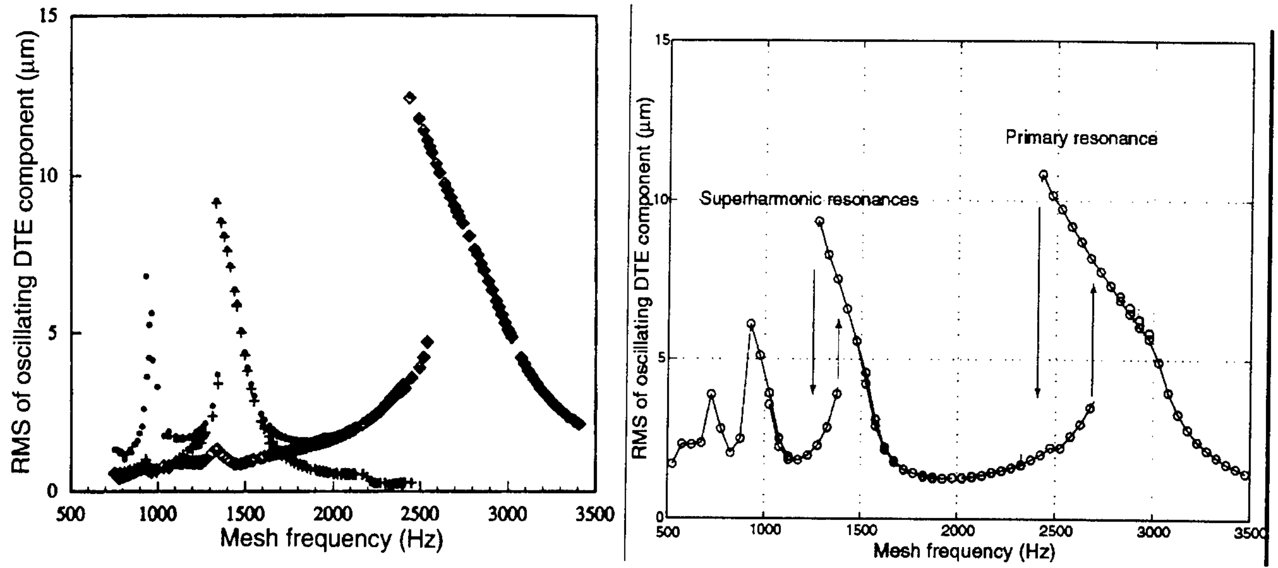

Figure 5: Dynamic response amplitude of a single-mesh gear pair for changing speed (i.e., mesh frequency). (a) experimental and (b) finite element.

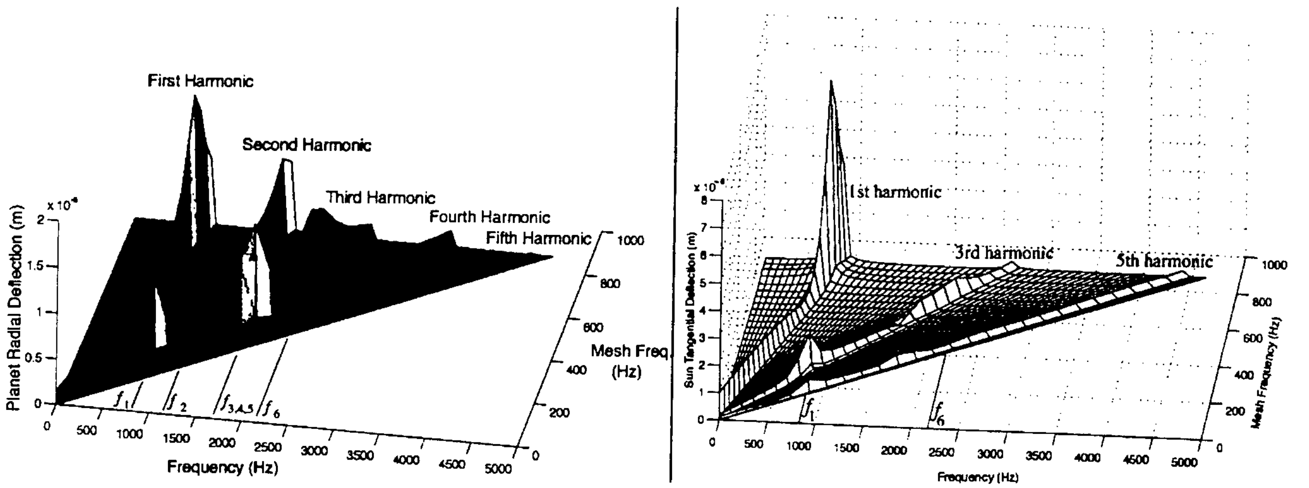

Figure 6: Spectrum of the dynamic response of a (a) planet gear and (b) sun gear for a range of operating speeds (i.e., mesh frequencies). The resonant peaks align exactly with the natural frequencies determined from the lumped-parameter model. Notice the absence of even harmonics of mesh frequency in the sun gear response. This can be explained analytically and used effectively for design purposes.

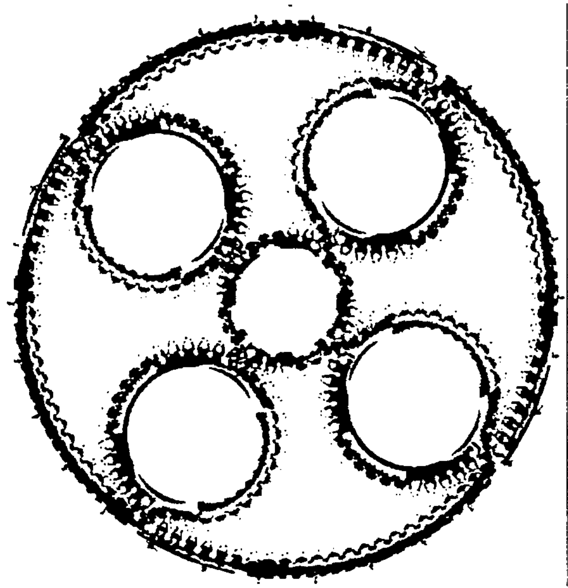

Figure 7: Tensile stress contours of the Army Kiowa planetary gear under dynamic operating conditions. Notice the large ring gear stresses that occur even far away from the planet-ring meshes; these indicate substantial and unexpected elastic deflection of the ring gear.

Natural Frequency (Hz)	Vibration Mode Type					
	Translational	Rotational	Planet	Translational	Rotational	Translational
Computational Model	778	1144	1729	1676	1723	2110
Analytical Model	774	1168	1694	1719	1782	2182
% Difference	0.5	2.1	2.0	2.5	3.3	3.4

Table 1: Comparison of natural frequencies from analytical and finite element models.